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(6) Heat Transfer to Compressible Fluids Flowing in Tubes at Supersonic Velocities.

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The primary objective of the project is to determine the local heat transfer coefficient from metal to air moving at supersonic velocities. It has been determined in previous investigations in the subsonic field that the definition of the heat transfer coefficient must be such that the coefficient does not vary with the temperature difference on which it is based. This temperature difference was found to be the difference between the actual wall temperature and the adiabatic wall temperature. To find this adiabatic wall temperature, it is necessary to use a concept known as the recovery factor. This factor is defined as the ratio of the difference between the adiabatic wall temperature and the mean stream temperature to the difference between the stagnation temperature and mean stream temperature. The recovery factors are computed from data taken during adiabatic runs. The determination of these factors is a secondary objective of the project.

A preliminary survey of the work done on recovery factors and heat transfer coefficients included reading pertinent NACA Technical Notes and Memoranda, ASME Transactions, and several MIT theses on heat transfer at subsonic and supersonic velocities. A detailed study was made of these by L. A. Nicolai, Lt. Commanders F. J. Grazieno and J. C. Smith, and E. L. Czapek as these were closely allied to the present problem.

The apparatus used by Smith, Graziano, and Czapek was available at the start of the investigation. While this was designed for subsonic velocities it was thought that preliminary work on this apparatus would help in eliminating faults in design, so that the apparatus for supersonic investigation would be yield more reliable data.

A study of Czapek's work revealed a need for more precise thermometry and for additional venting in the apparatus. The following changes were made:

1. Two additional air vents to the inner steam jacket were installed.
2. A previous installation was altered by connecting a manometer to the outer steam jacket and inserting a thermometer within the jacket to determine more accurately the inlet steam conditions.
3. Defective thermocouples were repaired and two quart thermos bottles were provided for the cold junctions.
4. A vernier was installed on the potentiometer scale and a more sensitive external galvonometer was substituted for the original one.
5. Vented steam is now conducted well away from the apparatus with rubber tubing.
6. Steam leaks in the apparatus were repaired and leaking collector-tube stopcocks were replaced.

Tests made after these changes seem to indicate improvements in the apparatus. While Czapek experienced a 5.3°F maximum temperature variation along the air tube in his full capacity heat transfer run, the present variation under similar conditions is 1.1°F. Better reproducibility and higher precision are obtainable with the sensitive galvonometer and vernier scale combination. In a special experiment at equilibrium conditions, the temperature of a single section was read each minute for fifteen minutes. The section previously showing the maximum temperature variation in this test varied from 221.0°F to 221.3°F, a percentage deviation of 0.14% while the most stable section varied from 221.0°F to 221.2°F, a

percentage deviation of 0.09%.

A detailed investigation of recovery factors indicated a need for a constant temperature air supply to the apparatus. To accomplish this, it was decided to run substantially constant temperature water from the canal of the M. I. T. Steam Laboratory through the shell of a cooler, and to pass the inlet air through the tubes of the cooler. The air then passes to a stagnation tank in which stagnation temperature and pressure are measured. From this tank, the air is metered into the apparatus test section. This arrangement resulted in a constant temperature supply of air to the apparatus. However, the air in the tank showed temperature stratification and, to determine precisely the condition of the air entering the apparatus, it was necessary to eliminate this stratification. The steps taken to accomplish this are summarized below:

1. Calculations were made to determine the smallest size tank which would give the air a velocity low enough to permit reading stagnation temperatures within the limits of precision of the equipment. The tank was small enough to limit the rate of heat transfer from the room to a comparatively low value.
2. Provisions were made for a temperature traverse of the tank by drilling a hole in the top surface and fastening a stiff rubber-fabric hose to this opening. A smaller hose, of diameter sufficiently large to fill the inside of this hose was inserted into it to cut down convection currents in the hose. The traversing thermocouple, and later, the differential thermocouples for recovery factor run, was passed through this inner hose, supported by a plywood rod which almost entirely filled the inner hose. The rod and thermocouple leads passed through a one-hole rubber stopper which completely closed the end of the tube. A small vacuum line was connected to the hose to draw out any layers of stagnant air that might form on the upper surface of the stagnation tank or in the hose.
3. The thermocouple leads were provided with an isothermal zone and were shielded from radiation.
4. The entire assembly of tank and cooler was covered with rock wool batt insulation varying from a minimum of eight inches to a maximum of thirteen inches, and shielded from radiation with an aluminum foil shield.

The tests of this stagnation tank showed a maximum stratification of the order of 0.2°F while some tests showed a stratification within the experimental precision of the potentiometer (about 0.05°F). This tank was considered to meet the requirements of a stagnation tank for the purposes of this investigation.

Examination of the results of recovery factor runs made at this time seemed to indicate two possible sources of error. The first was the possibility that, if the thermal capacity of the apparatus were the sole factor producing the discrepancies in the data, the time allowed for approaching equilibrium conditions was insufficient. Rough calculations showed this to be possible. The other possible source of trouble was that of heat being conducted into the apparatus through the insulation or along the metal legs and steam pipe from the warmer room. Calculations showed the total heat flux into the apparatus to be of the order of

5.5 Btu/hr about 60% of which flowed through the metal stand pipe.

An actual experiment was performed to test the sensitivity of the pipe wall temperatures to the heat flow through the stand. With the apparatus at equilibrium, Bunsen-Burner flames were applied to the legs, and after an hour they were withdrawn. Ice was then applied to cool the apparatus. The temperatures recorded during this test showed that the test pipe heated up and cooled, respectively, as heat or ice was applied to the stand.

As a result of this test it was decided that, to obtain true adiabatic conditions, the air temperatures along the outside of the pipe must be the same as those inside it. Several methods of accomplishing this approximately were discussed. One consisted of blowing air at a temperature equal to that in the stagnation tank through the inner Jacket of the rest section. It was thought that the stagnant air in the jacket would be appreciably warmer than the stagnation temperature of the air stream. However, measurement of this stagnant air temperature showed it to be only 0.2°F above the stagnation temperature. This is not a large enough difference to warrant the purging.

Another approach to true adiabatic conditions was made by placing one-quarter ($\frac{1}{4}$) inch thick wooden shims between the outer jacket and the metal stand. The steam pipe was removed and several more inches of rock wool insulation were added to the apparatus. The downstream stagnation tank was further insulated. These improvements cut down the heat flow into the apparatus by about 50%.

It was noticed that the pressures did not have the proper values. Calculations of the friction factors were made. From these calculations it was deduced that the nozzle of the apparatus was partially obstructed. Such a restriction would erroneously indicate a high rate of flow and this would affect the recovery factor values. After clearing the obstruction from the nozzle, the pressure readings returned to normal and the recovery factors were reduced to a more reasonable range.

Since the recovery factor is sensitive to the difference between the tube wall and room temperatures, it has been decided to make a plot of the difference between the stagnation and adiabatic wall temperatures, upon which the recovery factor depends, against the difference between the room and adiabatic wall temperatures. The points on the curve are to be obtained, for each Reynolds Number, by taking data at different room temperatures. By extrapolating this curve to zero temperature difference, the true value of the difference between stagnation and adiabatic wall temperature may be obtained. This will permit calculation of a true recovery factor.

Preliminary sketches of the apparatus for supersonic heat transfer have been made. These sketches do not represent the finished apparatus, but they do incorporate the improvements suggested by the results obtained in the present investigation. The sketches include the general arrangement of the jacketing of the apparatus, the provisions for measuring temperature and pressure, means of collecting condensate, and the venting arrangement. The problem of nozzle and tube design still has to be resolved.